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Impacts of climate and land use changes on flood risk management for the Schijn River, Belgium

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ABSTRACT

Flooding is the most common natural disaster in Europe. Modern flood risk management relies not only infrastructure development but also on governmental and non-governmental actors applying legal, economic and communicative water management instruments. Within the European Union (EU), flood management closely relies on policy set at the EU and national levels. It is now recognized that a sound understanding of climate change is required in addition to current management by taking into account land use change and socio-political context, as climate and land use changes have major impacts on hydrological responses.

This paper investigates the hydrological behavior due to urbanization under current and future climate scenarios of high summer and high winter rainfall for 20 sub-catchments of the Schijn River, located in the Flanders region near Antwerp, Belgium. As urbanization increases and existing rainfall-runoff models neglecting the specific behavior of urban runoff, a hydrological model was developed based on a basic reservoir concept and applied to the existing rainfall-runoff model (PDM) flow to examine the specific urban contribution. Results revealed that peak flow for urban runoff and the total peak flow (i.e. rural and urban runoff) were significantly higher (i.e. ranges from 200% to 500%) than the existing rainfall-runoff model (PDM) flows, because of faster and more peaked urban runoff response. The impact of climate change on current and future conditions was also assessed by estimating peak flows with respect to return periods from the flood frequency curve. The predicted peak flow of high summer future climate scenario was significantly higher (i.e. ranges from 200% to 250%) than that of the current climatic condition for this region. Furthermore, hourly peak flow and daily volume ratios of 100-year return period for the highest, lowest and average impervious area were projected for the time horizon of the year 2100. It is concluded that climate change impacts contribute the most in producing peak flow in coming years, while increased urbanization takes the second place for both hourly and daily values. Results on urbanization effect and climate change impact assessment are useful to the water managers for spatial planning, emergency planning and insurance industry.

1. Introduction

Flooding is the greatest economic natural disaster in Europe (Guha-Sapir et al., 2013) via damage and property and infrastructure, as well as physical injury and loss of life. As discussed below, EU flood policies took their roots in more than 100 major floods which occurred in the years 2000–2005 in Europe, among those, 9 floods were classified as extreme (Barredo, 2007). Major flood events resulted in 155 casualties and economic losses of more than €35 billion (Barredo, 2007). Material damage by floods in Europe in 2002 is estimated to be higher than in any previous year (Barredo, 2007). Damages caused by extreme floods have increased more than double in the last 50 years (Munich Re, 2005). (Feyen et al., 2009) estimated that economic losses caused by flooding in the EU are €6.5 billion per year, while the estimated annual damage is projected to rise to at least twice this amount by the end of this century. In May and June 2013, an extreme flood hits Central Europe in the Elbe and Danube River catchments and caused the highest water levels ever recorded (ICPDR, 2014). Subsequently, these floods highlighted the challenges related to Flood Risk Management (FRM) and fuelled the necessity for effective action programmes driven by policy in Europe. FRM is defined as a process of ‘holistic and continuous societal analysis, assessment and mitigation of flood risk’

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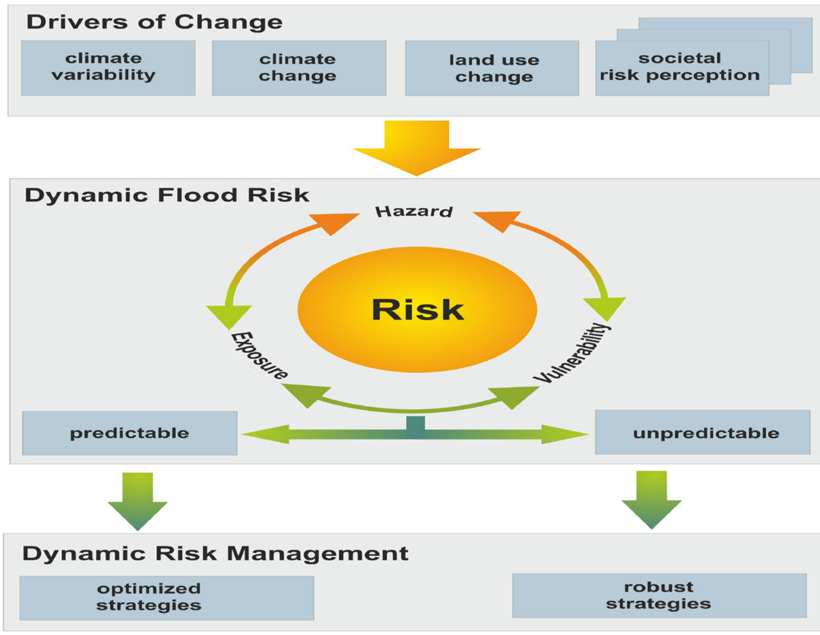

Fig. 1. Drivers of changes in flood risk, dynamic risk and dynamic flood risk management.
Source: (Merz et al., 2014).

(Schanze, 2006; Merz et al., 2010). It aims at managing the whole flooding system to reduce flood risks and providing environmental, social and economic benefits both for present and future (Sayers et al., 2014). In this case, accurate and updated data is necessary for decision-making and that's why the implementation of FRM strategies is quite challenging for practitioners, policy makers and researchers.

1.1. Dominating drivers of change for flood risk

The DPSIR model (EEA, 1999) is widely used to conceptualize environmental changes which set risk management rules. In this context, socio-economic developments are the driving forces (D), leading to environmental pressures (P) such as, increasing temperature and precipitation, which themselves lead to changes in environmental state (S) such as, inundation and flood, impact (I) refers to the effects on the environment of the pressures that are exercised on the system such as damage of property, ecosystem and loss of life, and response (R) consists of the actions taken to improve the status of the system by the society or policy makers such as strict rules for construction, maintaining natural floodplain etc. Some potential drivers of change are identified by (Merz et al., 2014) in Fig. 1.

Land use changes such as shifts from forestry to agriculture, from pasture to arable land, from rain fed to irrigated agriculture or from agricultural use to urbanized areas act as drivers for changes (EEA, 2016). Climate change impacts are increasingly considered in flood management along with other drivers such as, land cover changes and increasing water demand (Quevauviller, 2011).

In this respect, Global Climate Models (GCM) and Regional Climate Models (RCM) have shown that the magnitude and frequency of high precipitation extremes are likely to increase for Northern Europe and for Central and Southern Europe in winter (Dankers and Feyen, 2008; IPCC, 2013). For 2071–2100, projected precipitation extremes highlight an increase in Northern Europe, especially during winter (Kundzewicz et al., 2013) leading to increased flooding across most of North, Central and Eastern Europe (Lehner et al., 2006). Decreased flooding is projected for some parts of Central and Southern Europe (Dankers and Feyen, 2008). Alfieri et al., (2015) report that floods with return periods of 100 years are projected to increase double in frequency within 3 decades.

1.2. EU flood policy

At the European Union (EU) level, the water policy is governed by the Water Framework Directive (WFD), which aims to achieve good status for all waters in Europe (European Commission, 2000). The 2015 objectives have only been partly achieved in the 1st River Basin Management Plan (RBMP, 2009–2015) and are being now pursued in the 2nd RBMP (2015–2021). Flooding was not explicitly addressed in the WFD, nor climate change or its impacts. RBMPs represent the water management instrument and implementation of the WFD in all EU Member States. While climate change was not considered in the first cycle of RBMP (2009–2015), it has gradually been introduced in the policy discussions. In particular, climate impact has been discussed from 2009 onward through Common Implementation Strategy (CIS), composed of policy makers, experts from the Member States and of the European Commission (CIS, 2009) and recommended to integrate this dimension into the second (2015–2021) and third (2021–2027) cycles of RBMP (European Commission, 2013) to meet WFD goals under future projected climatic conditions. This approach is a kind of climate-proofing of the water policy (Quevauviller, 2014).

Recognizing the continued risks of flooding, specifically after the most devastating flood event in Central Europe in August 2002 and at the request of the EU Member States, the EC proposed the Flood Directive (FD) to set rules for the risk assessment and management of flooding (European Commission, 2007) in Europe. Complementing the WFD, the FD aims at reducing the adverse consequences of floods to human health, the environment and economic activity, taking into account the future changes in the risk of flooding as a result of climate change. Three steps are described in the EU Flood directive - preliminary flood risk assessment, flood hazard and risk map and FRM planning (Fig. 2).

As flood risk is not constant over time, flood risk maps and plans need to be revised every 6 years (De Moel et al., 2009) corresponding to the RBMP cycle. The principal information on flood and FRM at EU level is based on the reporting under the FD, which contains the Flood Hazard and Risk Maps and the draft of FRMPs i.e. flood-related action programs have to be embedded into the second RBMP (European Commission, 2015a). So the preliminary flood risk assessment would ideally consider climate change impacts and urbanization, that would

Fig. 2. Steps of flood risk management cycle described in the EU Flood Directive (European Commission, 2007).

have an impact on flooding consequences (European Commission, 2015b).

In this regard, many studies have been focused on the assessment of the impacts of future trends of land use and climate change at different scales on flood risk management (Klijn et al., 2012; Feyen et al., 2012; Alfieri et al., 2016). Most studies focused on the future flood risk assessment and estimation of flood related damages (De Kok and Grossmann, 2010; Feyen et al., 2009). Recent studies have investigated climate change impacts on hydrological responses e.g. (Ashraf Vaghefi et al., 2014; Teferi et al., 2015) indicating that climate change has a larger impact on the hydrological cycle than land-use change for the catchments like Schijn River (Kim et al., 2013; Khoi and Suetsugi, 2014). Therefore, it is indispensable to investigate the hydrological responses to land use changes under future climatic conditions. A variety of hydrological models, e.g., VHM (Willems, 2014), NAM (DHI, 2007), PDM (Moore, 2007) were used to simulate rainfall-runoff processes on a basin scale and used for climate change impact assessment.

1.3. Science-policy interfaces for flood management

Science policy interfacing plays an important role at a number of levels within the WFD context, including national, regional and local policy implementation. Several steps were undertaken by the EU to improve the interaction between science and policy through EU-funded research projects, which are considered to be an essential support to policies, particularly in the water sector (Quevauviller, 2010a). The FLOOD Site Integrated Project was carried out in 2004–2009 at the EU level and provided a solid knowledge basis for the development of the Flood Directive. This was complemented by improved knowledge on climate change impacts gained within the FP6 WATCH project and regional assessments with the CIRCE project. Further research actions focused on specific issues such as flash floods (IMPRINTS project), resilience (CORFU project), and governance (STARFLOOD project) etc. All these projects are described and referenced in Quevauviller et al., (2012b). The STARFLOOD project has informed the policy community about progress on FRM at EU level by regular contacts with the CIS Working Groups on floods, including scientists, flood risk managers and stakeholders. Thus, science-policy interactions seem to be an essential component (Quevauviller, 2010b) in the EU regulatory framework and need to be implemented in the second RBMP (2015–2021) and onwards.

1.4. Flood risk characteristics of Belgium

Floods occur in Belgium mainly due to tides and fluvial and pluvial runoff (Zagonari, 2013). In Flanders, the percentage of built-up land is expected to increase to 30–50% of land use (Poelmans et al., 2010) by 2050. Between 1976 and 2000, the urbanization ‘sealing’ process increased surface runoff by ~ 20% and with future developments, it will only increase (Poelmans et al., 2010). Annual precipitation has increased by 0.55 mm/year with a total increase of 94 mm/year in Flanders from 1833 to 2014, while the number of days with heavy precipitation has doubled since the 1950 s (VMM, 2015a). On average, about 800 mm rainfall annually falls in Low and Mid-Belgium and up to 1400 mm in High-Belgium (the Royal Meteorological Institute of Belgium (KMI)), 2013. There is already risk of urban pluvial flooding (e.g. extreme precipitation with heavy thunderstorms) in Antwerp (Uytven et al., 2015). Over 220,000 peoples are directly affected by flooding (VMM, 2015b). More than 67,000 citizens live in the area with medium probability of flooding (i.e. once in 100 years) and about 10,000 reside in the area with major probability of flooding (i.e. once in 10 years. The average annual flood damages in Flanders region of Belgium currently have exceeded 50 million Euros (VMM, 2015b). The Schijn River Valley and the Antwerp suburbs will always be more sensitive to pluvial than fluvial flooding due to the increased rate of urbanization and river systems with specifically dimensioned pumping stations and relatively open valleys. Moreover, climate change will lead to more likely frequent extreme summer storms so this effect is expected to increase in the future.

Hydrodynamic models (i.e. hydrology and hydraulics) are required to prepare flood risk maps. To fulfill the requirements of the EU Flood Directive by generating the flood risk maps, the PDM model (CEH Wallingford, 2000) is used as the hydrological component in the Info Works River System software (Innovyze) that simulates stream flow in the River. This PDM model works well for rural environments, but in urban environments, the urban drainage networks lead to faster runoff, creating a bi-modal response i.e. fast runoff from impervious areas and slow runoff from pervious areas (Dahl et al., 1996). In order to estimate river flows, both rural and urban runoff need to be calculated separately owing to large differences of the peak flows observed between rural and urban runoff (Dahl et al., 1996). This can be solved by using separate models for the urban and rural runoff in the same catchment by adopting an urban boundary (Vaes et al., 2009), an implementation of the Remuli model (Vaes,1999). Application of this urban boundary (Infoworks RS, Innovyze) can make a significant difference as e.g. observed on the Mandel River in Roeselare (Vaes et al., 2009).

In the past, fully integrated models, including urban drainage and river systems, as well as overland flow were built (e.g. Woluwe basin (HydroScan, 2016)). However, most currently available models include only river hydrology and hydraulics and do not include urban drainage network because the responsible river authorities are up till now only interested in the winter flooding from the rivers and not in the interactions with the urban drainage systems which are the responsibility of other authorities. Moreover, these detailed integrated models used for rivers as well as urban drainage require much more efforts and calculation time. So, it is chosen here to use very simple models with continuous long term simulations to maintain the first order accuracy (Vaes et al., 2001). This study demonstrated the influence of urban areas on the hydrological model flow for the Schijn River.

1.5. Implementation of EU flood directive in Flanders, Belgium

The Flemish legislature established the ‘Co-ordination Committee on Integrated Water Policy (CIW)’ to implement the WFD by adopting a Decree (18 July 2003). Prior to the EU Flood Directive, the CIW already introduced the FRMPs in Flanders through water assessments. The implementation of the FD just strengthened its

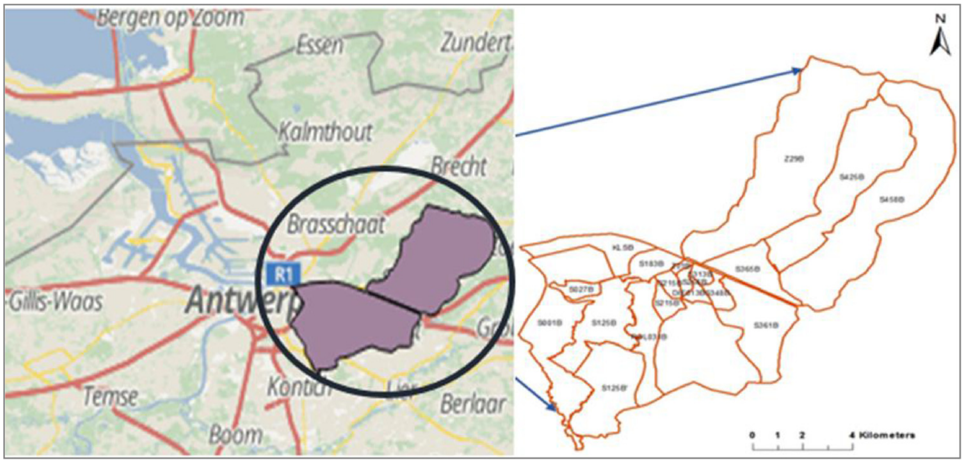

Fig. 3. Location of the Schijn River, Antwerp, Belgium (Schijn south is indicated by the arrows).

instruments (e.g. water test[1] by the water manager for every building permit within flood prone areas, duty to inform, signal areas and re-parceling with land swap) as well as measures (e.g. emergency intervention plan and general fire insurance). So, Flanders opted to skip the first phase of FD i.e. the preliminary flood risk assessment. They were able to make use of existing flood risk assessments and flood risk and hazard maps subject to certain conditions described in the Flood Directive (European Commission, 2012). Later on, Flanders decided to form an expert group within the CIW, which is responsible for flooding and cooperate with the working group of EC. Thus, the CIW plays the central role in planning and execution of water policy at the River basin level in Flanders. Taking account of reports required under the EU flood directive, flood hazard and risk maps for the Schijn River were published by the Flemish Environmental Agency (VMM) for low, medium or high probability in the case of the current climate, and a medium and high climate change scenario (VMM, 2016). Hence, the VMM can be considered as the active motor of the CIW in the integration of water management and spatial planning.

This paper presents an analysis of the existing flood risk management practices in the Schijn River based on the EU policy framework, assesses the peak flows under different scenarios taking into account both rural and urban runoff, evaluates the impacts of climate change on flood risk by analyzing peak flows and proposes new policy features and adaptation measures for flood risk management in the studied area.

2. Materials and methods

2.1. Description of the study area

The international Scheldt River originates in France, crossing Belgium and the Netherlands and discharging in the North Sea (Fig. 3). The River has a tidal influence, covering a gradient from salt to brackish to freshwater areas (Cox et al., 2006). The study sites are located on the Schijn River, a tributary of the Scheldt River. This small River with a mean discharge of 0.67 m^3/s, flows through the highly urbanized northern part of Belgium and enters the Scheldt River in the city of Antwerp (Wolfram et al., 2012). Among 44 sub-basins, 20 sub-catchments of the south part of the upper Schijn River covering 14 ha were considered for this study. The Schijn River was disconnected from its natural course by the installation of a concrete pipe and the diversion of 8 km northwards with pumping stations. So, tidal influence has been eliminated. The disconnection may have temporarily solved the flooding problems in the villages north of Antwerp, but this is not completely sufficient.

The study area is located on the edge of a metropolitan area, with significant increases in the residential land use that was once dominated by forest. The topography of the basin is generally flat. On the basis of the CORINE land cover map, the paved surface in the Schijn River was estimated as 19% of the total area, agriculture (19%) and grassland (9%) (IMDC, 2009).

2.2. Data collection

All of the required data except rainfall were obtained from the Flemish Environmental Agency (VMM). All of the GIS data such as, shape files of sub-catchments, boundary nodes, houses, streets and the River were collected from the Flanders Geographical Information Agency-'Large Scale Reference Database', an object-oriented reference map of Flanders with accurate and up to date information on urban areas (FGIA, 2016). Nearly 108 years (1901–2009) of hourly high-resolution local rainfall data were available as obtained from the climate change research group of KU Leuven, Belgium (HydroScan, 2016). The rainfall data were assessed for the Antwerp region based on the Uccle meteorological station, Belgium (Niel et al., 2015), where a perturbation tool (Ntegeka and Willems, 2009) was used to translate the observed original long time series (e.g. rainfall, ET_o) into future time series in order to be representative for the climate in 2100. In this study, two extreme climate change scenarios of high winter and high summer rainfall were used to investigate the future climate change effect. In addition to rainfall data, 108 years of hourly simulated PDM flow values were used for the current and future climatic conditions (HydroScan, 2016).

2.3. General characteristics of the PDM model

The Probability Distributed Model (PDM) is a lumped conceptual model for continuous rainfall-runoff developed by the UK Centre for Ecology and Hydrology, representing a variety of catchment-scale hydrological behaviors (Moore, 2007).

The model generates runoff at the catchment outlet by using rainfall (P) and potential evapotranspiration (E) as input based on a probability distributed soil moisture storage (S_1). Soil moisture storage generates direct runoff and groundwater recharge. Alternatively, the effective rainfall is divided into quick and slow pathways, which are routed via two parallel storage components i.e. surface storage (S_2) and groundwater storage (S_3) shown in Fig. 4. The simulated stream flow (q) by the

[1] Water test is an obligatory assessment asked by the government for new developments in order to check the impact of this developments on the water system (surface water and ground water). If there is a negative impact, this has to be compensated or permissions can be refused.

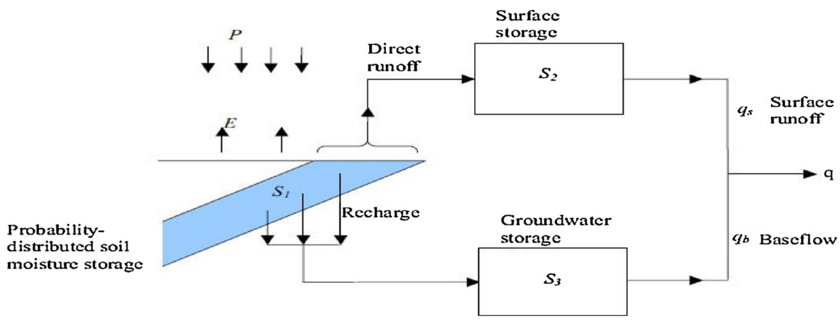

Fig. 4. Schematic view on the PDM rainfall – runoff model (Moore, 2007).

PDM model is determined by the sum of two pathways (q_s and q_b). The total stream flow is finally delayed to adjust the time to peak response.

2.4. The integrated hydrological model

The integration of the rural and urban runoff in a hydrological model was done using the existing runoff model (PDM) only for the pervious area (i.e. multiplying the flow by the ration pervious area over total area) and adding the runoff from the impervious area using a specific urban runoff model. For the urban runoff, a basic storage model was applied to take into account the non-linear behavior of the urban drainage system and the urban runoff was corrected based on time of concentration and flow through the sewerage systems. Both the original rural and integrated runoff volumes were made equal (i.e. the integrated model flow was obtained by adding rural and urban runoff together considering urban drainage systems and rivers systems).

2.4.1. Impervious area calculation

The first task was to calculate the percentage of impervious area in the southern part of the Schijn River basin containing the targeted twenty (20) sub-catchments. In Arc GIS, the total area of each of the twenty sub-catchments was calculated and the total urbanized area (houses, streets etc.) for each sub-catchment determined. The shape files of houses, streets were imported into the ArcGIS and the impervious area of each sub-catchment was calculated. Then the percentage of impervious area for each sub-catchment was calculated by the following formula:

$$Impervious\ area\ (\%) = \frac{Total\ impervious\ area\ (m^2)}{Total\ area\ of\ the\ subcatchment\ (m^2)} \quad (1)$$

2.4.2. Time of concentration

The time of concentration (T_c) is the time required for runoff to travel from the hydraulically most distant point in the catchment to the outlet. To calculate this, the flow path length is considered from the most distant point in the urban area to the river, because at the river, there will be the overflow for combined systems and outlets for rainwater systems. Urbanization usually decreases the time of concentration, thereby increasing the peak discharge (USDA, 2010). Time of concentration for calculating peak flow was calculated as follows (Endreny, 2005):

$$T_c = T_e + T_t \quad (2)$$

Where,

T_e = time of entry, time is taken for runoff to travel overland from properties, roofs, downpipe etc. to the point of entry at the road channels. This is the inlet time, whose values were considered 5 min, for small areas in a densely drainage urban situation.

T_t = travel time, being the time of network flow comprising time of flow in pipes and/or open channels, including the road channel, to the design point calculated as, L/U, where, L is the longest flow path length (m) and U is an average velocity of 0.8 m/s.

2.4.3. Urban runoff calculation

The Rational equation is the simplest method to determine peak discharge from drainage basin runoff and is the most widely used method for sizing sewer systems. The peak runoff was calculated as follows (Chow et al., 1988):

$$Q = 0.0028\,CIA \quad (3)$$

The Rational equation requires the following units (S.I):

C = Rational method runoff coefficient

I = rainfall intensity, (mm/h)

A = Catchment area, (m^2)

In order to calculate urban runoff, a runoff co-efficient (C) was assumed as 0.95. The addition of a simple reservoir model was taken into account for the storage in the sewer system in urban runoff calculation (Fig. 5).

The throughflow, Q_{uit} is estimated as 0.5 mm/h and the maximum storage, V is 5 mm for Flanders. When the storage is filled the remaining inflow is supposed to overflow into the river. An attenuation on the

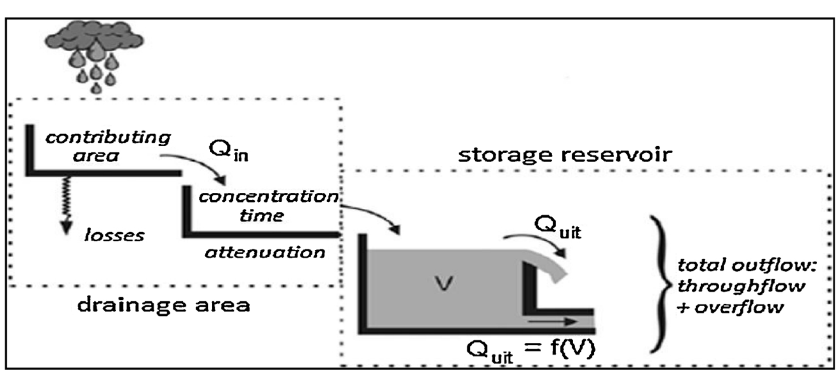

Fig. 5. Continuous conceptual model for urban drainage systems or storage facilities.
Source: (Vaes, 1999).

runoff Q_{in} (calculated with Eq. (3)) is used to take into account the time of concentration. This means that when the rainfall is higher than 0.5 mm/h the storage starts to fill and the through-flow is limited to an equivalent of 0.5 mm/h until the storage is full and the overflows start working, i.e. discharging the remaining flow (Vaes, 1999). All those values are based on past experiences in similar catchments of Flanders by Flemish experts.

2.5. Statistical processing of data

2.5.1. Data aggregation

The hourly simulated PDM flow values and the integrated model flow (i.e. rural runoff and urban runoff) for both the current and future climate (e.g. high summer and high winter) were aggregated by using the moving window approach in excel worksheet. Six aggregation levels of 1 h (i.e. original time series), 3 h, 6 h, 12 h, 24 h and 48 h were used. This was done to examine the variation of flow along the river at different times of concentration.

2.5.2. Selection of independent extreme peak flows

The extreme value analysis and QDF model are based on nearly independent extremes (i.e. peak values) extracted from the full time series. These independent extremes were obtained by a peaks-over-threshold (POT) approach. This was done by using independence criteria based on threshold values for the time between two successive independent extreme peaks, the ratio of the minimum flow between the two peaks over the peak value and the peak height (Willems, 2009). The details about the equations and parameters of the POT selection tool used in the study can be found by using a 'POT selection tool' (Onyutha and Willems, 2015a, b).The POT values were calculated for all the PDM and integrated model flow of the above-mentioned aggregation levels for the whole study area and for all scenarios.

2.5.3. Extreme value analysis

After POT value extraction from the time series, the ranked (i.e. from highest to lowest) POT values were imported into the hydrological extreme value analysis (ECQ) tool (Willems, 2004) for each aggregation level. The tail of each of the extreme values was analyzed for flood frequency curve. Parameter values for extreme value distribution with a right tail were obtained by visualizing the fitting of the Q-Q plot and slope Q-Q plot. It was found that the distribution has a normal tail (i.e. exponential distribution) for all of the aggregation levels. Then, the extreme value distribution of each aggregation level was calibrated by selecting an optimal threshold value for a Q-Q plot. Once the extreme value distribution was done in the ECQ analysis, calibration parameters were used to calculate the peak flows for each aggregation level with respect to a return period. The peak flow values of different return periods were found for each aggregation level with the following equations:

$$T = \frac{n}{t}\left[\frac{1}{[\exp(\frac{x-x_t}{\beta})}\right] \tag{4}$$

$$x = x_t - \left[\left(ln\frac{n}{T*t}\right)*\beta\right] \tag{5}$$

Where,

x = flow for the corresponding return period (m^3/s)
x_t = optimal threshold flow (m^3/s)
β = scaling factor or slope of the exponential distribution (m^3/s)
T = return period (years)
n = total number of years
t = total number of exceedances of the threshold level, x_t

Then, the graph of extreme values with respect to return period provided the flow with corresponding return period by extrapolation. In this case, a 100-year return period was chosen for all of the aggregation levels. Flows for the return period of 5 and 25 years were also calculated for high, low and average percent impervious area.

2.5.4. Flood frequency analysis

Flood frequency is the average interval between floods that have a flow value above a given threshold or the probable frequency of occurrence of a given flood (Siwila et al., 2013). The hydrological extremes (i.e. floods) are commonly assessed by the frequency analysis (Fotakis et al., 2014). The plot of estimated flow versus return period at different durations is the outcome of the statistical processing of flow. Thus, the flow duration frequency (QDF) curves allow the calculation of extreme event quintiles as a continuous function of duration and return period with a straightforward formula.

3. Results and discussion

3.1. Analysis of flood risk management practices in the Schijn River

The prominent paradigm for Flanders is 'creating space for water' and the basic principle of 'retaining, storing and discharging' moved towards 'Multi-Layer Water Safety' (MLWS). The MLWS focuses on the 3 P approach - prevention, protection and preparedness in FRM that brings shared responsibilities among actors. The Schijn River is classified as non-navigable category managed by VMM.

To manage flood risk for the Schijn River, there are four concepts such as, avoiding downstream flooding, restoring fish migration, retaining a watercourse that has maximum visibility and increasing the gravity drain are practiced. In recent years, VMM, Aquafin, the city of Antwerp and the province of Antwerp have taken a number of measures to avoid flooding in the Schijn River, such as, placing three additional pumps in the sewage treatment plant Merksem, making adjustable siphons for the Groot Schijn under the Albert canal, closing the siphon of Klein Schijn under the Albert canal, sanitation of the sludge from the Schijn vaulting and opening the partition between the various sleeves, construction of a pumping station at the beginning of the Schijn vaulting with a capacity of 10 m^3/s and separating the watercourse by a dike from the outflow of the vaulting to the pumping station Rode Weel over a length of 5.9 km.

Good practices were established in the Schijn River by analyzing the FRM of Flanders. The reform of the water test in 2012 significantly improved the efficiency and effectiveness of the instrument. The duty to inform the property buyers about flood risk is a versatile tool, which is inexpensive and easy to implement for increasing flood awareness among inhabitants. Obtaining compensation from the governmental disaster fund for flooding used to be a lengthy and complicated procedure in Flanders (Bruggeman, 2010). Designing effective flood insurance was a difficult task because it raised ethical questions about solvability, solidarity and personal responsibility. There is solidarity built into the flood insurance coverage, as all citizens contribute to this coverage, regardless of their location.

An ambitious FRM policy can succeed by addressing gaps between policy makers and local actors at federal, regional or provincial level. As FRM is developed in a top-down manner, when a new initiative is designed at the regional level, participation of local authorities is limited. Since the local actors are mainly responsible for the implementation of the initiative, their adoption is often lacking in the field because municipalities are unaware of their existence or are incapable or unwilling to apply them. It is sometimes difficult for local authorities to strictly follow building codes in flood prone areas. Currently, there exists only weak coordination between the insurance industry and the policy makers. Because different flood risk maps are being used for different preventative instruments. Also because insurance sector is uncomfortable with their profit than the implementation of a premium system which would incentivize citizens to take action on the level of their property. The natural disasters are only responsible for a marginal

part of the total fire insurance premium so there is little gain for insurers.

Traditionally, flood risk management in Belgium is regarded as a governmental responsibility. However, the discourse is emerging which emphasizes the necessity to share responsibilities concerning FRM with the citizens at large. If the government wants to continue with this new approach, it will have to convince its citizens. However, instruments and measures help to limit further construction in flood-prone areas but existing risks would remain and increase due to climate change. Devroede et al., (2013) found that depending on the catchment's characteristics and spatial planning practices, the economic risk can increase from 7 up to 100% and the social risk[2] can increase from 13% to 132%. Therefore, it seems important to incentivize people to take action on the level of their flood-prone properties.

3.2. Urbanization effect on flood risk

3.2.1. Degree of imperviousness

Percentages of impervious area for all of the twenty (20) sub-catchments were calculated (Fig. 6). The maximum and minimum impervious percentages were ≈ 46% for the sub-catchment SCH001B and 8% for the sub-catchment SCH215B respectively. The average impervious area of these sub-catchments was calculated as 20%. The sub-catchment (ROL031B) has 17% impervious area, which is close to the average and thus was used in the further investigation to represent the average condition.

The time of concentration (T_c) for the twenty (20) sub-catchments was also calculated from the longest flow paths. The values of T_c were within the range of 1 h to 4 h, with most cases about 1 h. That is because the highly urbanized area reduces the time of concentration values.

3.2.2. Urbanization influences on PDM model flows

The differences among the original simulated PDM flow, corrected PDM flow (rural runoff), urban runoff and the integrated flow (i.e. rural and urban) provided by a simple integrated hydrological model in the Schijn River basin are displayed in Fig. 7.

It can be clearly seen that urbanized area provided the largest peak flow of 0.80 m^3/s, whereas the integrated flow (i.e. rural and urban) calculated by the integrated model was found to be 0.89 m^3/s and the original simulated PDM flow was 0.12 m^3/s only. Urbanization may increase runoff volumes and peak flows by the removal of the vegetation and the soil compaction. Moreover, in urban areas, the value of the runoff coefficient i.e. the proportion of the precipitation that enters in a stream is relatively high, while it is low in the rural areas, especially in the forest. Hence, urban and rural catchments of the same size and topography will react differently to the same amount of precipitation. The peak flow in the urban area is usually higher and the time-to-peak is shorter than in the rural areas. Similar concepts were observed by (Kundzewicz, 2012).

3.2.3. QDF model

The QDF relationship curve of the original PDM and integrated model flow for the sub-catchment Sch001B under the current climate scenario is shown in Fig. 8 (a). The aim of this task was to compare the predicted flow of the original simulated PDM flow with the calculated integrated model flow if the climatic condition is constant. Fig. 8 (a) shows that about 5 times higher peak flow was observed for the integrated model flow than the original simulated PDM flow with respect to three return periods of 5, 25 and 100 years, which shows the large need of integrated models for rivers in urban areas. For instance, the peak flow was estimated at 1.8 m^3/s for a 100-year return period and at 1 h aggregation level for the PDM flow; whereas the flow was increased as 9.8 m^3/s for the integrated model flow of the corresponding return period and aggregation level. Note that flow values increase with increasing return period, which means that the occurrence of extreme events increases with a higher recurrence interval. Again, the flow decreases with increasing the aggregation level of the same return period. Even at 48 h of aggregation level, the flow values of different return periods come closer. The same trend was observed for all of the aggregation levels and for all sub-catchments.

The flow analysis done here was for the PDM flow and the integrated model flow, which would help to understand the flood characteristics of the study area, floods from sudden high peak flows in one hand and on the other hand floods from more long duration moderate runoff. The design of hydraulic structures such as dams and reservoirs can be optimized depending on different possible extreme conditions and can also be assessed from the QDF plots (Mujumdar and Kumar, 2012), which can be also used for designing controlled flood areas.

The effect of return periods on the predicted peak flows was also investigated in Fig. 8 (b). In doing this, the flow ratio of the integrated model and the original PDM model as a percentage (%) of a sub-catchment were used for 3 return periods of 5, 25 and 100 years. Fig. 8 (b) shows that the flow ratio of the integrated model and the PDM is slightly higher for a return period of 5 years (T_5) than for a return period of 25 (T_{25}) and 100 years (T_{100}). So, we conclude that there is little impact of using different return periods on the predicted flow ratios of integrated flow and PDM flow. Because the urban system reacts rather linearly for higher return periods and there is a direct link between rainfall intensity and resulting peak flow.

3.2.4. Co-relation with imperviousness

By calculating predicted peak flows at six different aggregation levels for all of the sub-catchments, the correlation of peak flows with imperviousness are shown in Fig. 9.

Blue dots represent 1 h aggregation level, red dots 3 h, green dots 6 h, purple dots 12 h, light blue dots 24 h and yellow dots 48 h. Fig. 9 shows that the correlation coefficient (R^2) is relatively low, but still there is a global tendency, despite the fact that other local urban runoff aspects play an important role too. The scatter on the results is mainly caused by the fact that urban drainage systems are complex and tailored designed towards the specific local situations.

3.3. Impact assessment with climate change

For future climate scenarios, the impact of CC was evaluated under the assumption that the present rate of urbanization is constant. That means for a future scenario, land use changes or more specifically, extent of urbanization was assumed to be the same as present. This is not in accordance with the urbanization forecasts, but the Flemish legislation has built in extensive compensation measures for building projects that creates at least a sort of stand-still in runoff effects (i.e. applying sustainable urban drainage systems and compensating storage). The same analysis was done for all of the 20 sub-catchments and this is given as appendix. As the building regulations compensate the effect of the increased urbanisation on the runoff, the assumptions of constant urbanisation will only lead to second order effects on the results.

3.3.1. Climate change impact on peak flows

The impact of climate change was assessed by analyzing the estimated peak flows of the current climate and the two extreme scenarios of high winter and high summer rainfall as future climatic conditions for the sub-catchment SCH001B (Fig. 10).

Blue line indicates estimated peak flows of high summer for 100 year return period at different aggregation level. Similarly, green and red lines indicate respectively high winter and current climate peak flows for same return period. Fig. 10 shows that the predicted peak

[2] Unemployment, substandard health and education services, **social** rejection, various types of crime, poor housing and bad territorial management may be considered as **social risk**.

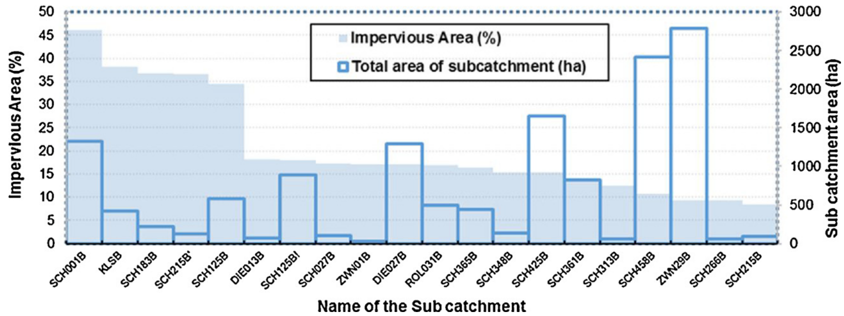

Fig. 6. Impervious area percentages for each sub-catchment in the Schijn River, Antwerp, Belgium.

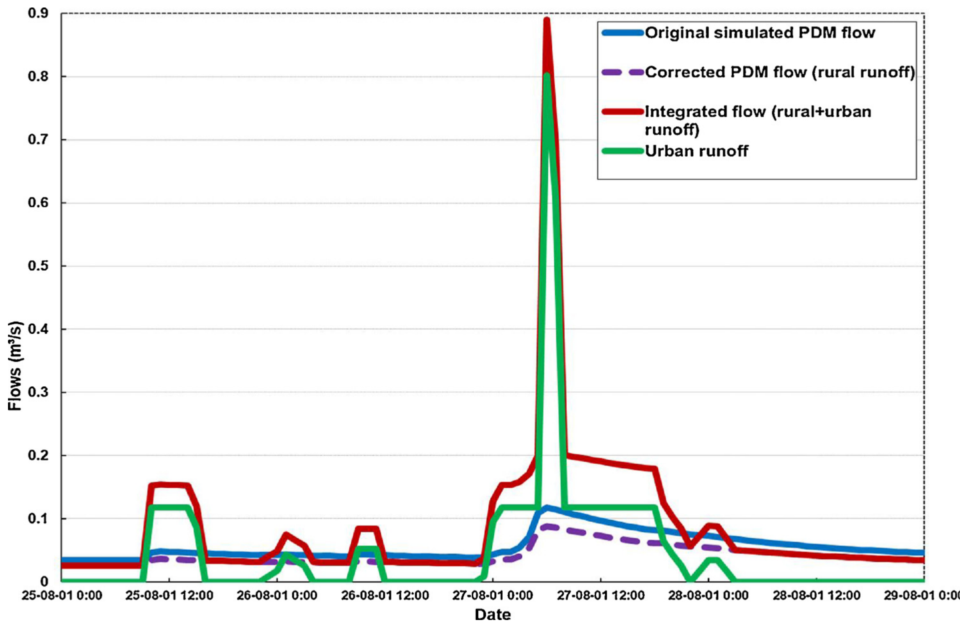

Fig. 7. Differences of the Original simulated PDM flow and the Integrated flow: example from the sub-catchment ROL031B representing average (17%) urban area.

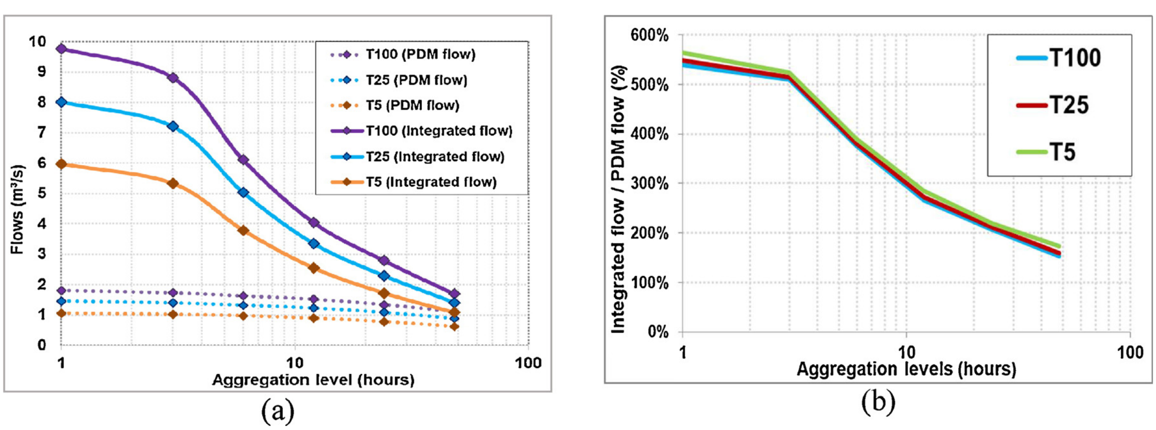

Fig. 8. (a) QDF curve of original PDM and Integrated model flow for sub-catchment SCH001B under current climate (b) Effect of different return periods on flow of sub-catchment SCH001B.

flows are nearly equal for high winter and current climatic condition whereas for high summer scenarios, flows are more than 2.5 times higher than those. This is because summer storms are typically short but heavy. The occurrence of heavy rainfall events is usually less frequent during winter. The flooding in the Schijn River is mainly derived from rainfall runoff from the upstream impervious area. Extreme summer storms are more violent and the more extreme the rainfall event, the more violent their change will be (Tabari et al., 2015). The peak flows may double for responsive waterways in sloping or heavily paved areas under a high climate scenario over 100 years (VMM, 2016).

3.3.2. Projected change of flows in future climate

Attempts have been taken here to check how much urbanization could influence the PDM model flow that is applicable to rural runoff together with changing climate for the time horizon 2100. In this regard, a baseline year was introduced to serve as a reference year (i.e.

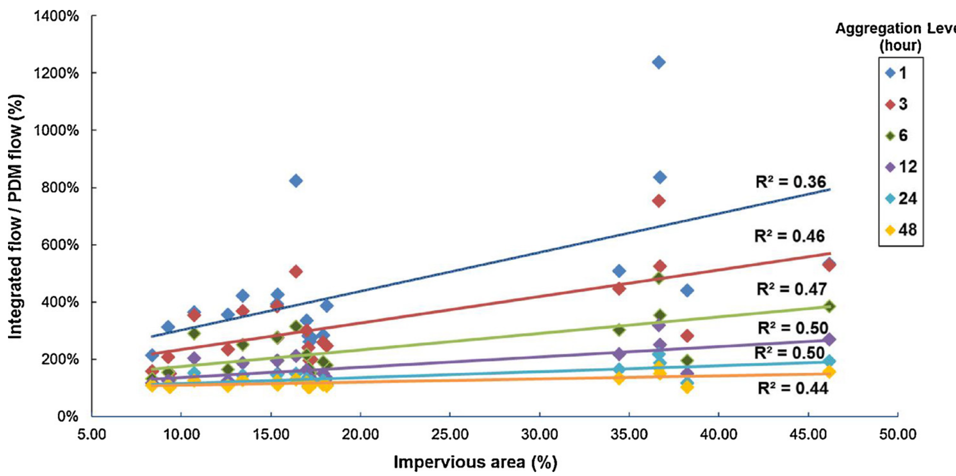

Fig. 9. Co-relation of predicted peak flow ratios with imperviousness of the sub-catchments of the Schijn River, Antwerp, Belgium (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

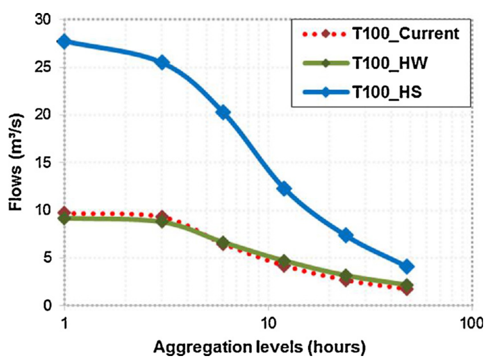

Fig. 10. Differences of peak flow between current and future climate scenarios of high summer and high winter for the sub-catchment SCH001B at T_{100} (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

from the climate perspective the historical rainfall series that is used as representative for the year 1975).[3] The calculation was done for high (46%), low (8%) and average (17%) percentage of impervious area based on 100 years return period for hourly and daily values.

The hourly PDM flow is projected to be 64% for future high winter and ~300% high summer scenario at the end of this century with respect to the reference year 1975 (Fig. 11 a). At the same time, the integrated peak flows decrease 28% for high winter and increase 990% for high summer by 2100. Since the imperviousness is almost half of the sub-catchment SCH001B, the flow increased by 433% accounting for intensified urbanization. On the other hand, the flow is projected to increase by 94% due to the urbanization effect (Fig. 11 Fig. 11b) for 24 h aggregation. Both the daily PDM and integrated flow changes were found very high at 2100 for high summer and the difference between those are 141%, whereas for high winter scenario, this difference is only 62%.

For average impervious area (ROL031B), the hourly PDM flow might vary 100%–164% but the integrated flow even could decrease 9% in case of high winter and the difference between PDM and integrated flow was found 549% for high summer (Fig. 12 a). For the same sub-catchment at 24 h aggregation level, the differences are very small. For high winter, it was found 27% and for high summer, it was 73% only (Fig. 12 b).

[3] The 100 years' time series (1901-2009) that is used for the calculation has at the end already some climate change effect, which makes that this time series is representative for 1975 in terms of climate effect.

In the case of lowest urbanized area, the hourly change of peak flow for urbanization was found 115% (Fig. 13 a). Again, the PDM flow might increase 66% for high winter and 349% for high summer, whereas the integrated model flow might only increase 8% for high winter and 453% for high summer. The 24 h aggregation level in both the PDM and integrated flow of high winter and high summer are almost similar for the same sub-catchment (Fig. 13 b), the urbanization effect plays a role on the short durations.

In order to check climate impact only, an analysis of the change in peak flow of the integrated model was also done by the flow ratio between the reference year and the future climate change scenario of high summer and high winter for the return period of 100 years for hourly and daily values.

It can be noticed that hourly peak flow ratios with respect to the urbanization effect increased highly with increasing impervious area but with respect to the climate change effect they decreased very slowly for high summer and high winter in function of the degree of urbanization (Fig. 14a). The increasing and decreasing trends for daily flow ratios (Fig. 14b) was found similar as hourly but the highest summer extremes were observed here.

3.4. Proposed policy features and adaptation measures

The policy implementation should consider actions vertically and horizontally within the federal, state and local governments by considering the following approaches.

Technical approach - The technical area should focus on the prediction of floods, the economic value of properties in flood prone areas, and development and modelling of flood risk and hazard information.

Social approach - Public perception of flood risks should be explored, including how people have adapted their lives to living with the impact of climate change and how to communicate flood risks with communities and decision makers. Different dissemination techniques can be utilized such as school projects and broad information media intended to reach a large number of people e.g. newsletters, leaflets, seminars, websites, flood alarm systems etc.

Planning approach - The planning approach identifies how to provide better information to spatial planners and politicians, through decision support systems and investing in real life demonstration developments. De Moel et al., (2015) reviewed different approaches to flood risk assessment, which is necessary for any measure before implementation. On the other hand, it may not be beneficial to implement all FRM Strategies simultaneously. In this context, a few adaptation measures through the processes of MLWS are suggested below.

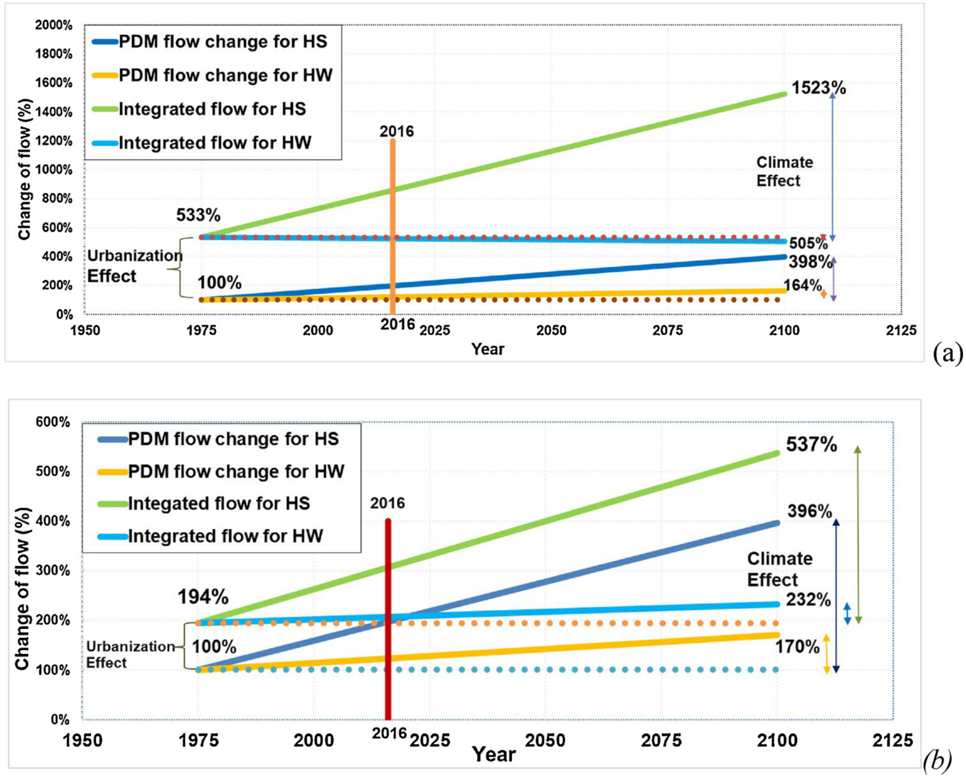

Fig. 11. (a) Future projection of hourly peak flow ratios (%) for the PDM and integrated flow for highest impervious area (SCH001B) (b) Future projection of daily runoff volume ratios (%) for the PDM and integrated flow for highest impervious area (SCH001B).

A Spatial Adaptation Measures

Compartmentalization is a technique that can be used to reduce flood risks by dividing large flood areas into smaller ones by slowing down the flooding or guiding the flow to an area where it does least damage, potentially reduces the adverse consequences of a flood (Klijn et al., 2010). Also, land-use zoning approach can be used to mitigate flood risk by prohibiting residential and industrial building in flood-

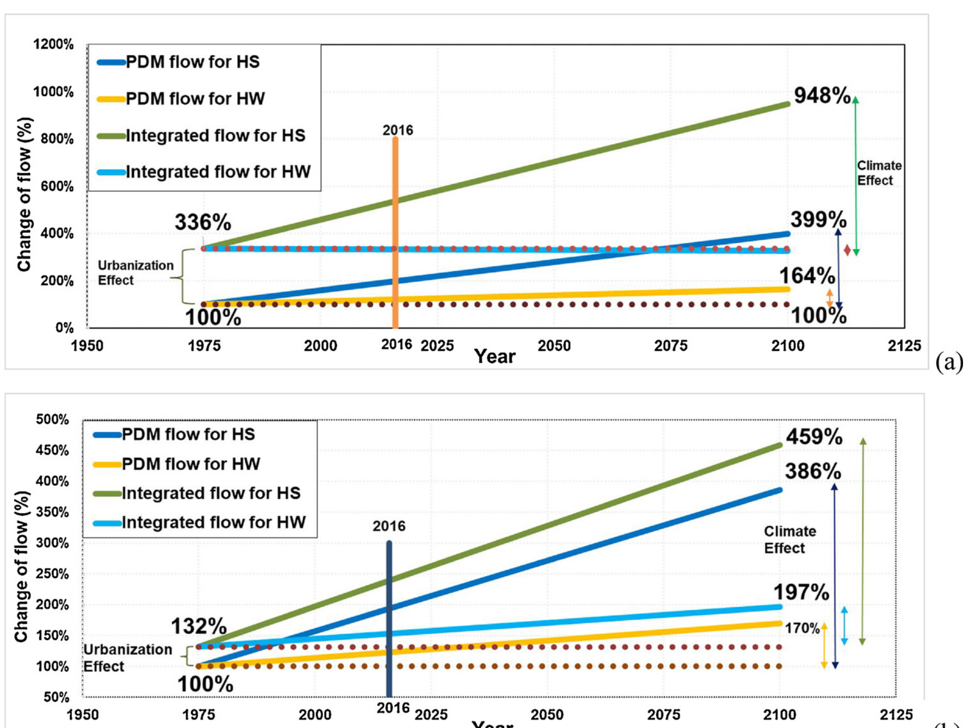

Fig. 12. (a) Future projection of hourly peak flow ratios (%) for the PDM and integrated flow for average impervious area (ROL031B) (b) Future projection of daily runoff volume ratios (%) for the PDM and integrated flow for average impervious area (ROL031B).

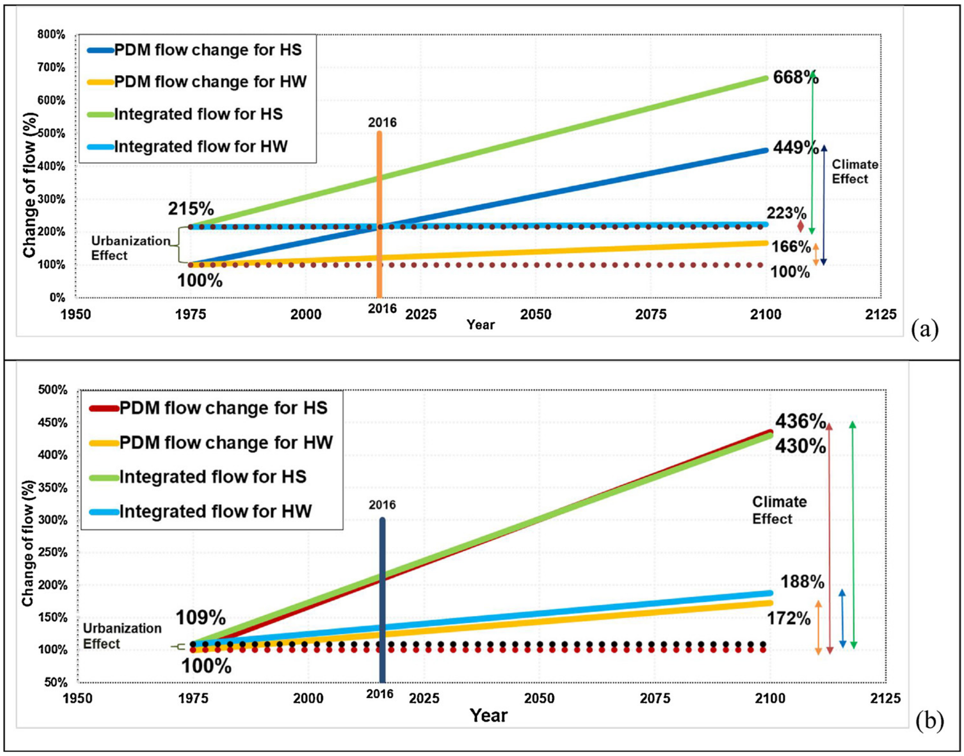

Fig. 13. (a) Future projection of hourly peak flow ratios (%) for the PDM and integrated flow for lowest impervious area (SCH215B) (b) Future projection of daily runoff volume ratios (%) for the PDM and integrated flow for lowest impervious area (SCH215B).

prone areas. Areas with a high flood probability can be developed as nature or recreational purpose.

For uncertainty of the impact of climate change, it is important to preserve space for additional measures in the future and to design current measures taking this uncertainty into account. This means that a retention basin should be constructed in such a way that it's through-flow and its capacity can be adapted without exuberant investments in the future. For the Schijn valley, this could mean that the new pumping station towards the Albert Canal should be able to be extended with additional pumps in the future and this should already be taken into account in the current design.

Despite these preventive and protective measures, flooding will still occur due to existing buildings. Therefore, it is important to construct the new buildings in such a way that flooding can be prevented, to provide existing buildings with property level flood protection and to have a government assisting technically and financially in these measures. The resilient building is one of the most important and effective measures to prevent flood damage. Existing flood-prone buildings can be protected by watertight bulkheads for doors and windows, non-return valves on drains, sealing holes in the wall, providing a barrier to underground garages, installing buffers or sumps and making waterproof interior by a concrete or tile floor rather than a wooden floor. Such measures will often not be able to protect completely but the damage will be limited to an acceptable level. The inhabitants will indeed have an increased self-reliance and will be able to resume daily life after a flood more quickly.

- Cost-Benefit analysis for FRM

The use of cost-benefit analysis in FRM requires expert knowledge from both economists and engineers to determine the level of safety. The benefits of a flood protection system are the avoidance of casualties, damages and losses and these can be comparable with the costs of the protection system.

- Climate dikes for flood protection

A super levee or climate dike originated from Japan is a broad river embankment which can withstand overflow (Fig. 15). It prevents

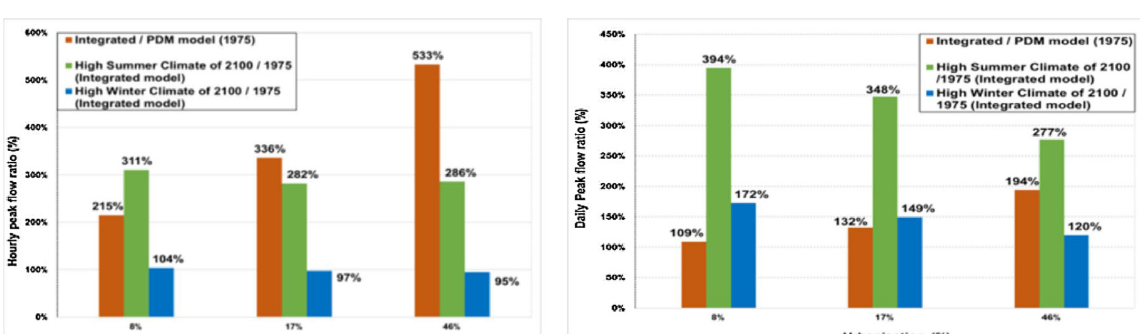

Fig. 14. (a) Changes of hourly peak ratios (%) at different impervious percentage for the Schijn River, Antwerp, Belgium (b) Changes of peak ratios (%) for daily runoff volumes at different impervious percentages for the Schijn River, Antwerp, Belgium.

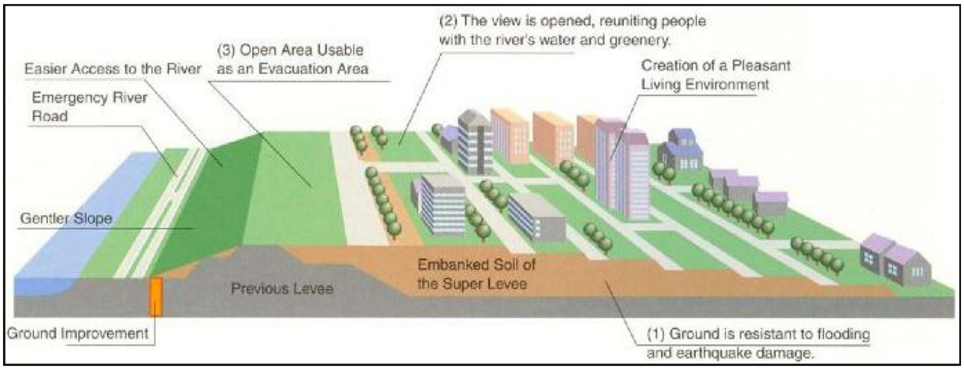

Fig. 15. Cross section of a conventional embankment design and a super levee design (Valin, 2009).

uncontrolled flooding due to a dike breach. The slope of the embankment is made very gentle. So, if the river rises the above the embankment, the water would spill gently down the slope. The embankment is protected from destruction and serious damage to assets along the river is minimized.

However, the responsibility for prevention is with not only the higher authorities or local authorities. Also, citizens can avoid potential damage to their private property by taking appropriate measures such as disconnection, storage and infiltration of rainwater in their field or the installation of green roofs.

4. Conclusions and recommendations

For an effective FRM policy, the impact of land use and climatic change on flood risk for the Schijn River in Belgium was investigated. The following conclusions can be drawn from this study.

Urbanization has increased significantly since the last decades along the Schijn River, reaching one-third to half of the sub-catchment area. A high degree of land sealing decreases rainwater infiltration, thereby making it more vulnerable to flooding. The integrated hydrological model clearly shows that using a single mode rural runoff model underestimates significantly the peak runoff flows and this underestimation is higher for areas with more imperviousness. The underestimation will again decrease when taking into account the river hydraulics (i.e. the more downstream the more it decreases) and this is also observed in the larger aggregation levels. However, although it is a rough first order integrated model, it shows that locally large differences in peak flows in the river will occur. Runoff volumes will rise with higher urbanization area and a bit decreases for low urbanized area.

The results demonstrate that the flood risk will increase significantly with both urbanization and climate change. Highest runoff volumes were observed for high summer scenario for all of the cases. Future projections of high summer indicates that the hourly integrated model flow increases very significantly from low to high impervious area and the corresponding daily values rises comparatively slow. The climate change impacting runoff decreases slowly with increasing urban area for both the hourly and daily runoff volume ratios.

Past spatial planning practices did not enable to fully tackle the flood risk. An ambitious flood management policy nowadays needs to be designed with lessons learnt from these past experiences. Different spatial planning instruments such as, the water test, signal areas, compensation of urban peak runoff by local storage may help to limit further construction in flood-prone areas but cannot entirely control this. They cannot change enough the existing situation, certainly not with respect to the extreme events and the increased impact with climate change. Therefore, it is important to incentivize homeowners to make their own homes more resilient through property level flood protection or to even buy up the most flood-prone buildings and remove them.

The general recommendation from this study is that the flood risk management strategies must be accomplished locally and need to be developed in consultation with local stakeholders and the inhabitants who are at risk. A sustainable FRM policy should be based on a shared responsibility through collaboration with long-term economic and environmental benefits and social acceptance in Belgium. Effective flood risk management will only work with public participation and need based measures. The concept of updating flood risk management, three steps of measurement, modelling and management could be followed to monitor the evolution and impact of climate change. This would allow engineers and policy makers to continuously adapt design criteria and even more important to make adaptive designs, such as, building retention basins with the possibility to the extent its capacity in the future without exuberant investments if climate change would demand so.

Besides the major infrastructure and the local measures, drainage and storage systems should be designed taking into account the most recent climate scenarios. Although measures that have already been taken in the downstream part of the Schijn River are very strong, the overall condition of peak drainage of the Schijn River is still debatable. The three-stage strategy of retaining, storing and draining should be brought up in practice. This includes the maximum retention and creation of canals in the execution of sewerage projects.

Flow prediction for a range of precipitation intensities is at the core of flood risk management. QDF curves of different aggregation levels and of different return periods can help policy makers to make decisions for adaptation strategies related to flood prediction in order not to underestimate the peak runoff from urbanised areas.

The detailed of risk quantification, prediction and management system for urban pluvial flooding is very complex compared to fluvial floods occurring in major rivers and requires the accurate measurement and prediction of local rainfall over short periods of time (i.e. minute to an hour). More detailed models are required to find out the local flood effects in urban areas where rivers and urban drainage and overland flow heavily interact.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2018.07.002.

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